Three chances for entropy

Michael Pohlig – Joel Rosenberg

100 years of entropy as heat

pohlig@kit.edu jrosenberg@berkeley.edu

Prologue

Prologue

“In my opinion, Mrs. Wendell—and I believe Dr. Steinmuth will concur—if you can live with entropy you can live with anything.”

Ed Fisher, *The New Yorker*, 17 October 1977

Prologue

"In my opinion, Mrs. Wendell—and I believe Dr. Steinmuth will concur—if you can live with entropy you can live with anything."

"The concept of entropy is anyway one of the most occult concepts in physics."

H. Heuser – 2010

Ed Fisher, *The New Yorker*, 17 October 1977

Prologue

Entropy can be introduced in a way
"**which any schoolboy could understand**"
H.L. Callendar – 1911

Callendar
(1863-1930)

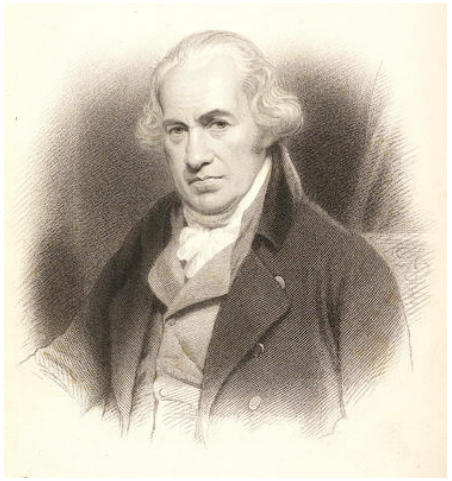
Ed Fisher, *The New Yorker*, 17 October 1977

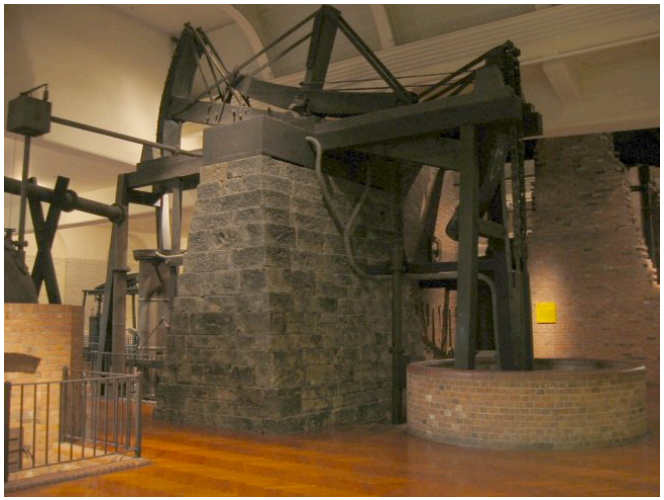
Joseph Black
(1728 – 1799)

1st Chance

Joseph Black
(1728 – 1799)

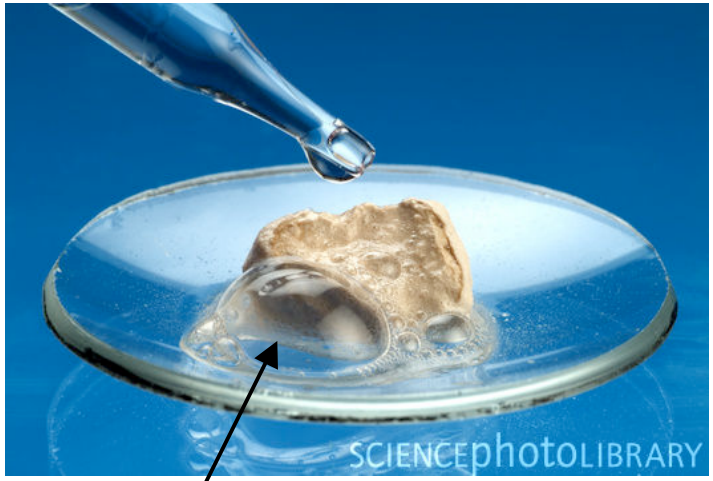
James Watt
(1736 – 1819)





http://www.theglasgowstory.com/images/TGSB00331_m.jpg
http://192.197.62.35/staff/mcsele/newcomen.htm

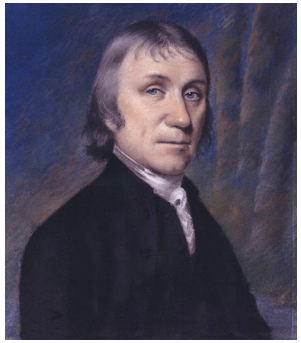
Joseph Black
(1728 – 1799)



"fixed air" (carbon dioxide)
released by adding acid to chalk

http://www.sciencephoto.com/media/4674/enlarge

Joseph Black
(1728 – 1799)



Joseph Priestly
(1733 – 1804)

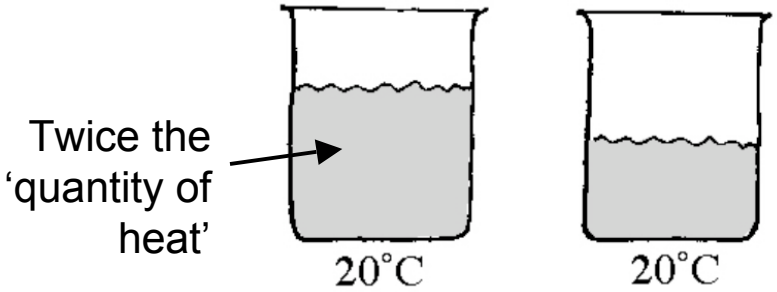
Henry Cavendish
(1731 – 1810)

Antoine Lavoisier
(1743 – 1794)

http://en.wikipedia.org/wiki/Joseph_Priestley
http://ffden-2.phys.uaf.edu/211_fall2010.web.dir/Smith_Elliot/About_Cav.html
http://en.wikipedia.org/wiki/File:Antoine_lavoisier.jpg

"Intensity of heat" (temperature) vs. "quantity of heat"

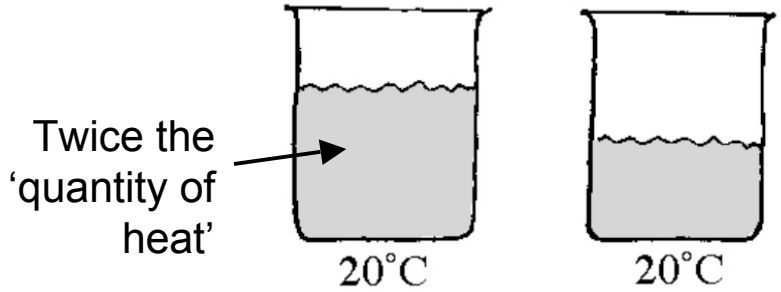
1st Chance



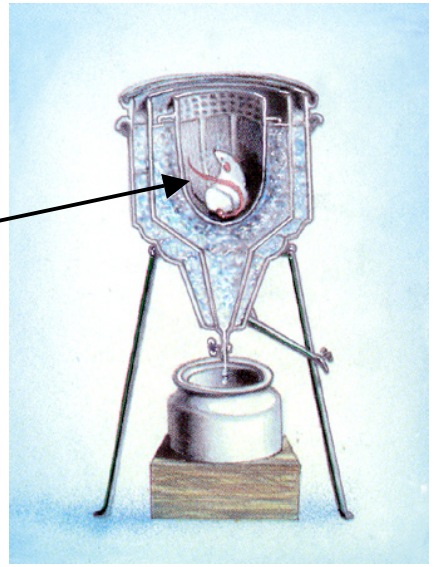
"*If, for example, we have one pound of water in a vessel, and two pounds of water in another, and these two quantities of water are equally hot, as examined by a thermometer, it is evident, that the two pounds must contain twice the* ***'quantity of heat'*** *that is contained in one pound."*

“Intensity of heat” (temperature) vs. “quantity of heat”

1st Chance



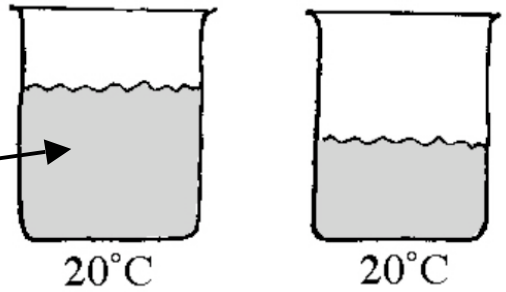
Latent heat



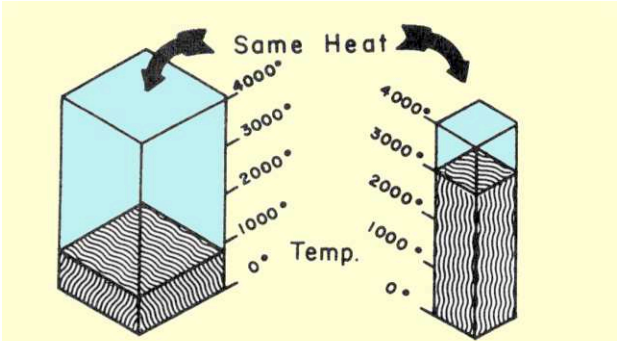
http://www.nature.com/scitable/content/ice-calorimeter-developed-by-lavoisier-and-laplace-14898943

"Intensity of heat" (temperature) vs. "quantity of heat"

Twice the 'quantity of heat'



Heat capacity

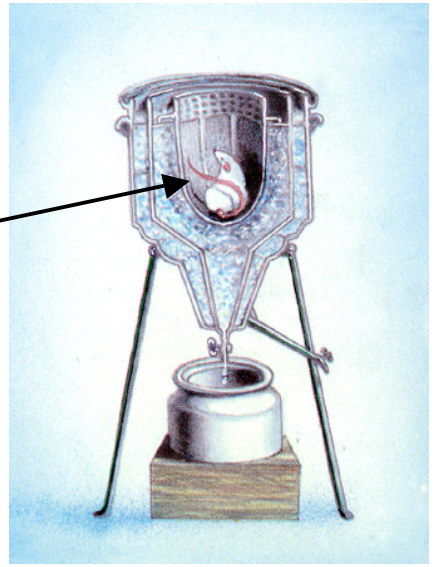


Large heat capacity (e.g. water)

Small heat capacity (e.g. mercury)

Latent heat

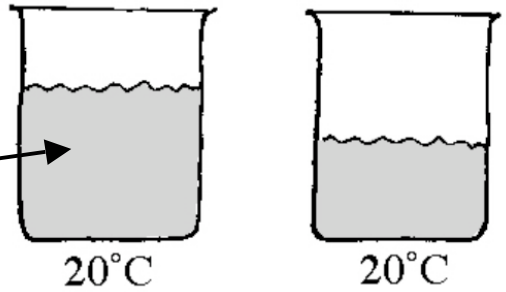
Mouse in ice calorimeter



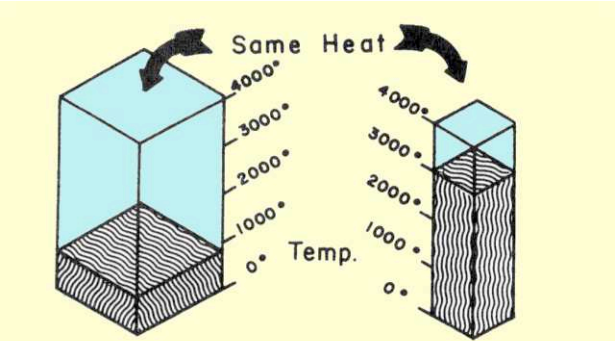
"*Quicksilver...requires less heat to heat it, than that which is necessary to heat by the same number of degrees an equal measure of equally cold water.*"

"Intensity of heat" (temperature) vs. "quantity of heat"

Twice the 'quantity of heat'



Heat capacity



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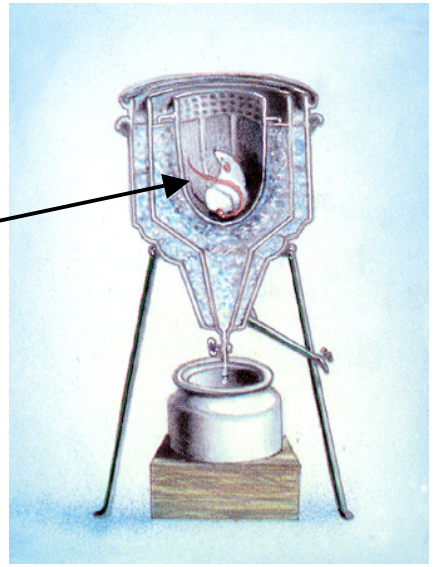
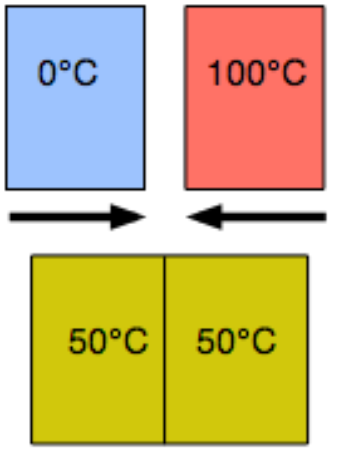


Thermal Equilibrium



http://www.chem1.com/acad/webtext/chemeq/Eq-01.html

1st Chance

"*When we perceive that what we call heat disappears in the [melting] of ice, and reappears in the [freezing] of water, and a number of analogous phenomena, we can* ***hardly avoid thinking it a substance****…*

"But since heat has never been observed by us in a separate state, all our notions of this union must be hypothetical."

1783: Lavoisier's "Table of Simple Substances"

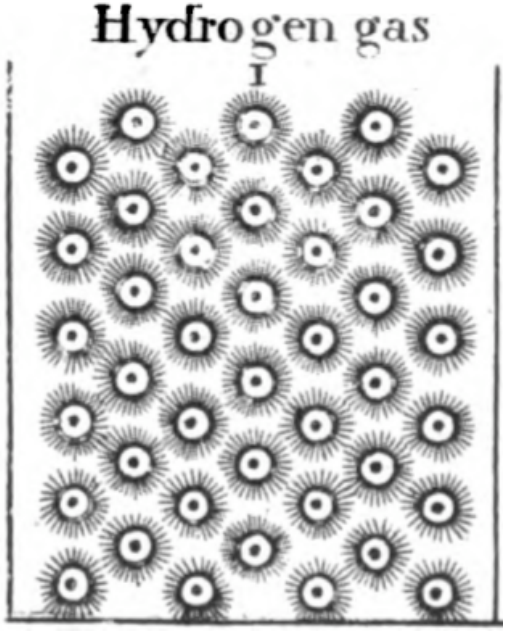
	Noms nouveaux.	Noms anciens correspondans.
Substances simples qui apprtiennent aux trois règnes et qu'on peut regarder comme les élémens des corps.	Lumière.	Lumière.
	Calorique	Chaleur.
		Principe de la chaleur.
		Fluide igné.
		Feu.
		Matière du feu et de la chaleur
	Oxygène.	Air déphlogistiqué.
		Air empiréal.
		Air vital.
		Base de l'air vital.
		Gaz phlogistiqué.
	Azote.	Mofète.
		Base de la mofète.
		Gaz inflammable.
	Hydrogène	Base du gaz inflammable.
Substances simples non métalliques, oxidables et acidifiables.	Soufre.	Soufre.
	Phosphore.	Phosphore.
	Carbone.	Charbon pur.
	Radical muriatiq.	Inconnu.
	Radical fluorique.	Inconnu.
	Radical boracique.	Inconnu.
	Antimoine.	Antimoine.
	Argent.	Argent.
	Arsenic.	Arsenic.
	Bismuth.	Bismuth.
	Cobalt.	Cobalt.

Antoine Lavoisier
(1743 – 1794)

Traité Élémentaire de Chimie, http://books.google.com/books?id=-KkO-8zd1voC

1783: Lavoisier's "Table of Simple Substances"

	Noms nouveaux.	Noms anciens correspondans.
Substances simples qui apprtiennent aux trois règnes et qu'on peut regarder comme les élémens des corps.	Lumière.	Lumière.
	Calorique	Chaleur. Principe de la chaleur. Fluide igné. Feu. Matière du feu et de la chaleur
	Oxygène.	Air déphlogistiqué. Air empiréal. Air vital. Base de l'air vital. Gaz phlogistiqué.
	Azote.	Mofète. Base de la mofète. Gaz inflammable.
	Hydrogène	Base du gaz inflammable.
Substances simples non métalliques, oxidables et acidifiables.	Soufre.	Soufre.
	Phosphore.	Phosphore.
	Carbone.	Charbon pur.
	Radical muriatiq.	Inconnu.
	Radical fluorique.	Inconnu.
	Radical boracique.	Inconnu.
	Antimoine.	Antimoine.
	Argent.	Argent.
	Arsenic.	Arsenic.
	Bismuth.	Bismuth.
	Cobalt.	Cobalt.

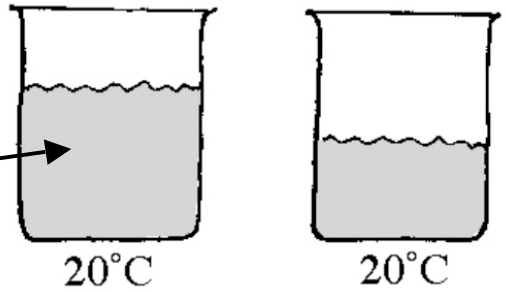


Francis Bacon
(1561 – 1626)

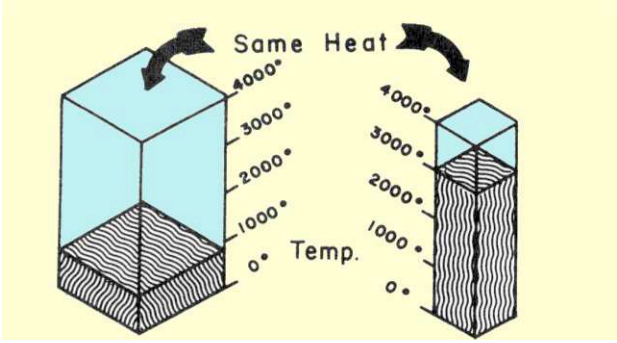
http://en.wikipedia.org/wiki/Francis_Bacon

"Intensity of heat" (temperature) vs. "quantity of heat"

Twice the 'quantity of heat'



Heat capacity

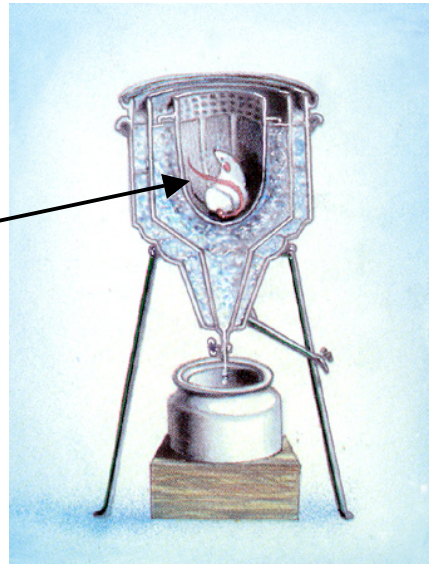


Large heat capacity (e.g. water)

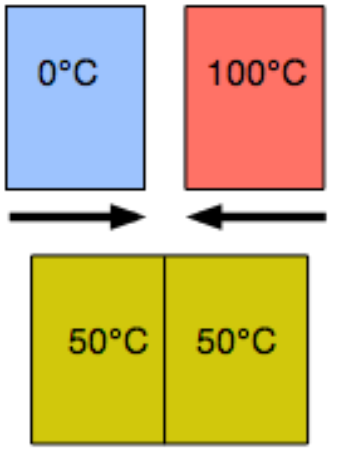
Small heat capacity (e.g. mercury)

Latent heat

Mouse in ice calorimeter



Thermal Equilibrium

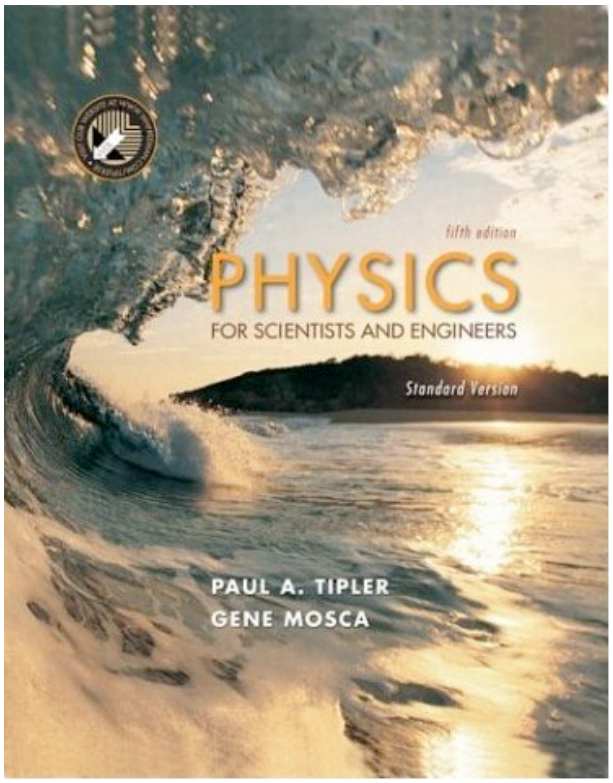


1st Chance

"It is correct, then, to say that a system has a large amount of internal energy, but it is not correct to say that a system has a large amount of heat or a large amount of work. ***Heat is not something that is contained in a system.*** *Rather, it is a measure of energy that flows from one system to another because of a difference in temperature."*

Tipler, 2003

Paul Tipler

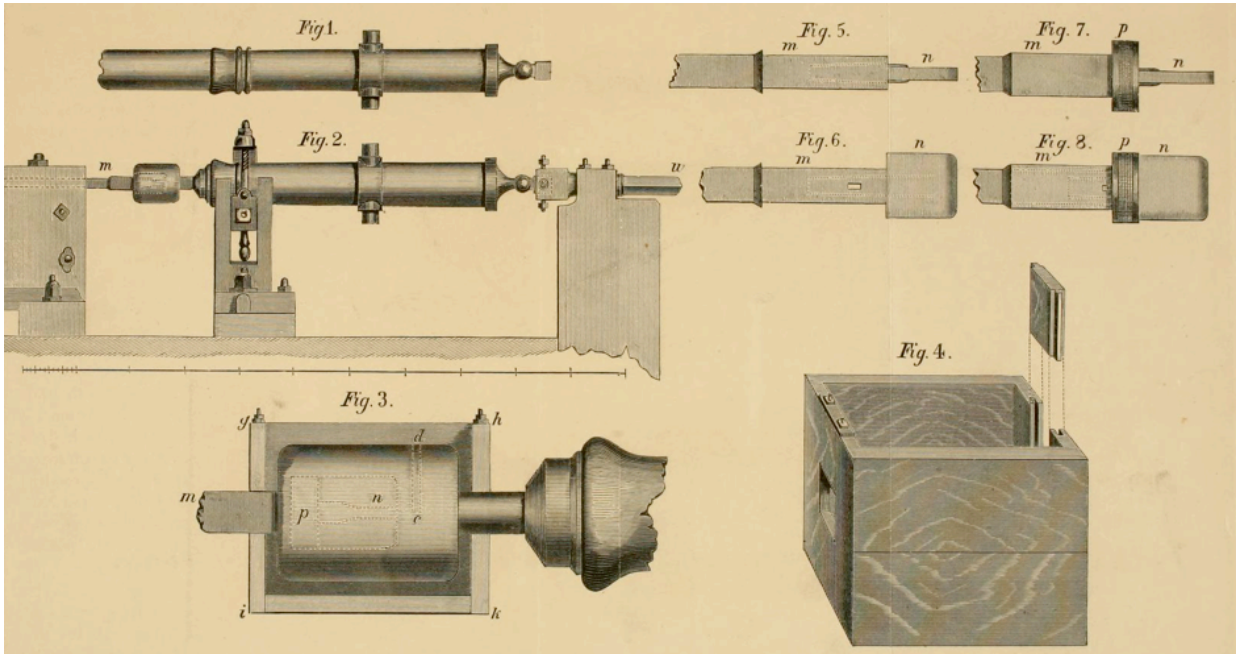


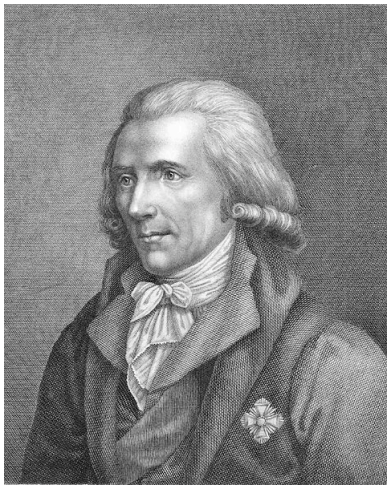
“Creatio ex nihilo”

You can’t create something from nothing

1798: Rumford's Canon Boring Experiment

1st Chance



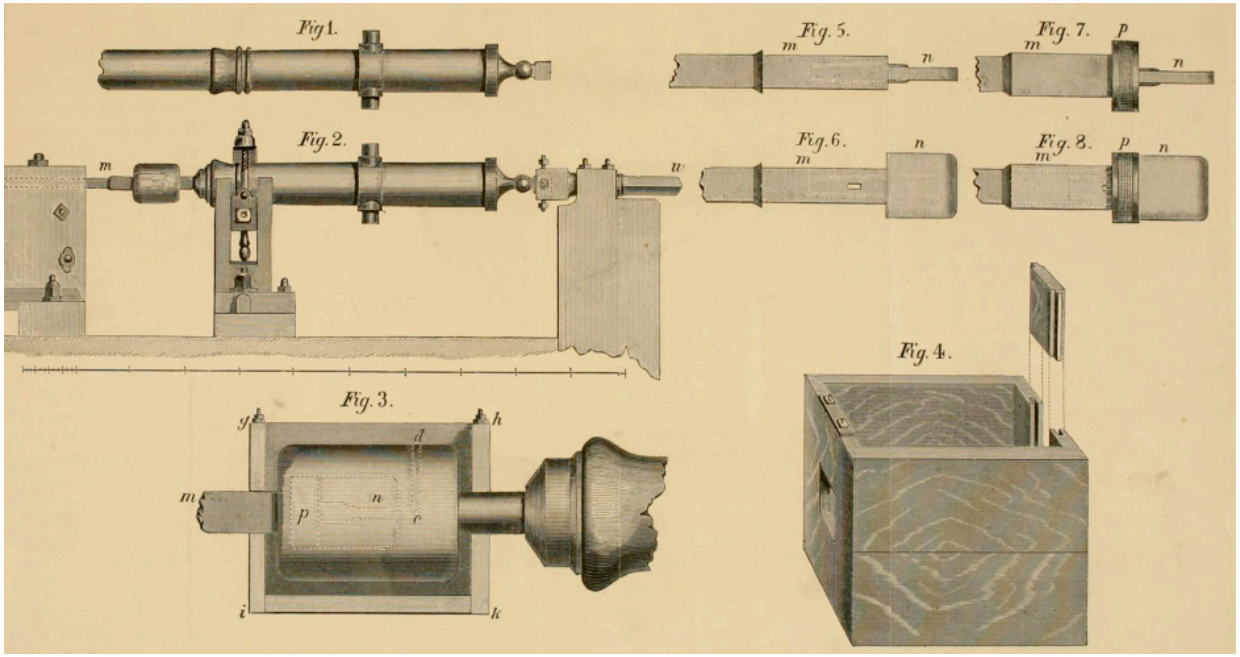


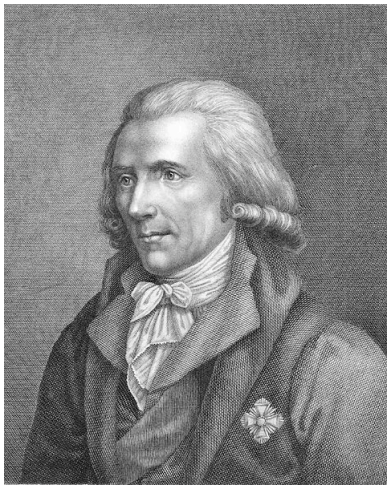
Count Rumford
(Benjamin Thompson)
(1753 – 1814)

1798: Rumford's Canon Boring Experiment

1st Chance

"Anything which an insulated body or system of bodies can continue to furnish without limitation, cannot possibly be a material substance."

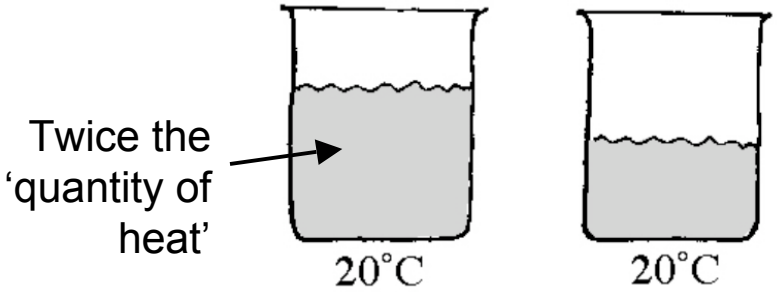




Count Rumford
(Benjamin Thompson)
(1753 – 1814)

"Intensity of heat" (temperature) vs. ~~"quantity of heat"~~ entropy

1st Chance



"*If, for example, we have one pound of water in a vessel, and two pounds of water in another, and these two quantities of water are equally hot, as examined by a thermometer, it is evident, that the two pounds must contain twice the* ~~***'quantity of heat'***~~ *that is contained in one pound."*

entropy

Sadi Carnot
(1796 – 1832)

2nd Chance

Sadi Carnot
(1796 – 1832)

Lazare Carnot
(1753-1823)

http://www.eoht.info/page/Lazare+Carnot

1824: Carnot's Heat Engines

2nd Chance

1) Is there a fundamental limit for the improvement of heat engines?

2) Are there agents preferable to steam for developing the movitve power of heat?

Reflections on the Motive Power of Heat
http://en.wikipedia.org/wiki/File:Grazebrook_Beam_Engine.jpg

1824: Carnot's Heat Engines

2nd Chance

1) Is there a fundamental limit for the improvement of heat engines?

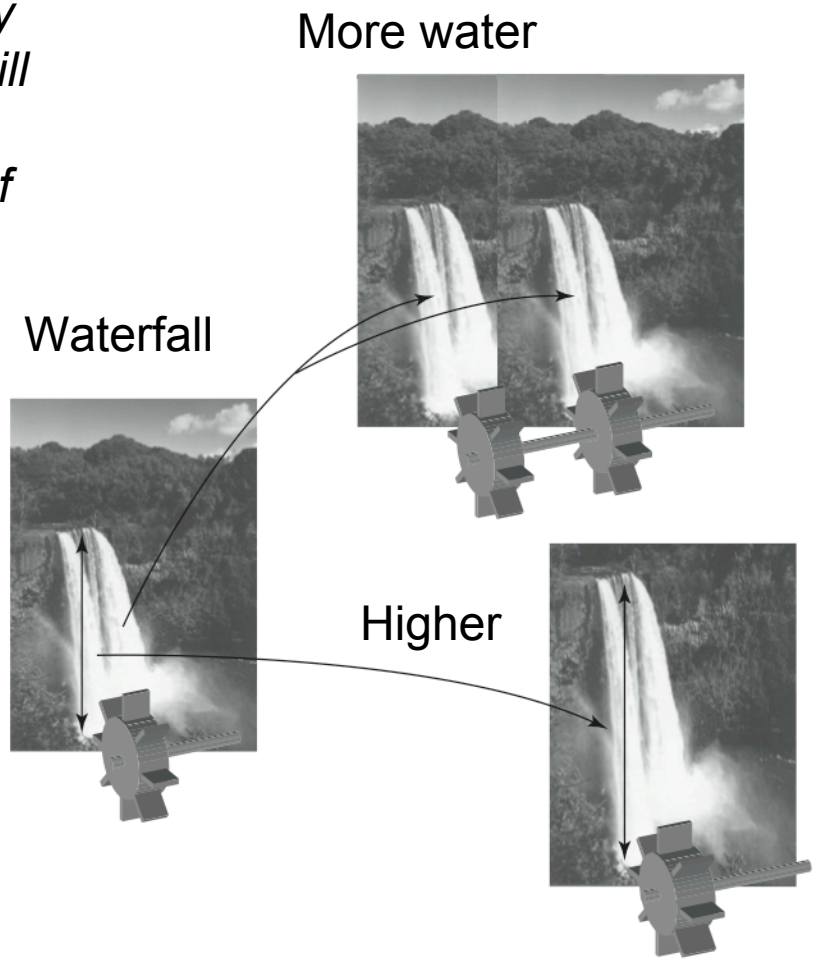
2) Are there agents preferable to steam for developing the movitve power of heat?

"The production of motive power is …due in steam-engines not to an actual consumption of caloric, but to its transportation from a warm body to a cold body, that is, to its re-establishment of equilibrium."

Reflections on the Motive Power of Heat
http://en.wikipedia.org/wiki/File:Grazebrook_Beam_Engine.jpg

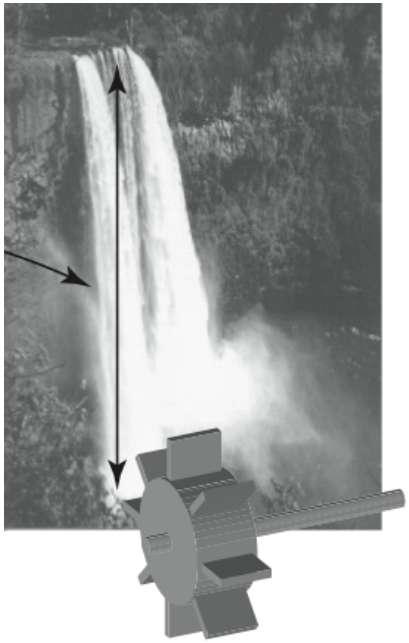
2nd Chance

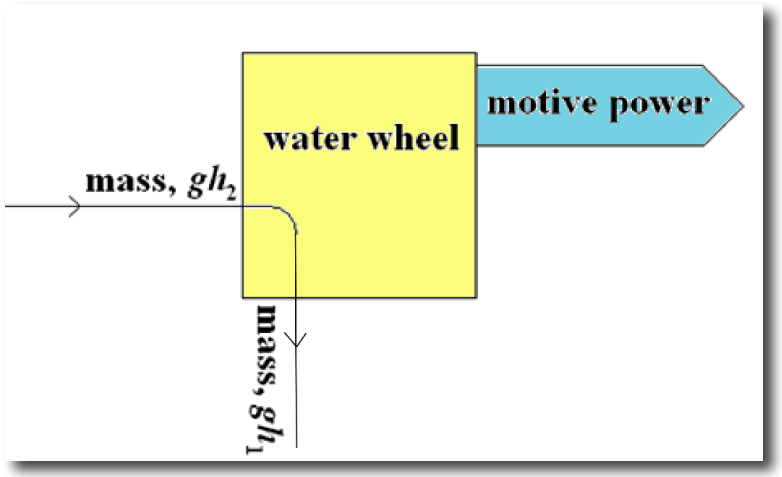
"The motive power of a waterfall depends on its height and on the quantity of the liquid; the motive power of heat depends also on the quantity of caloric used, and on what…we will call, the ***height of its fall,*** *that is to say, the difference of temperature of the bodies between which the exchange of caloric is made."*

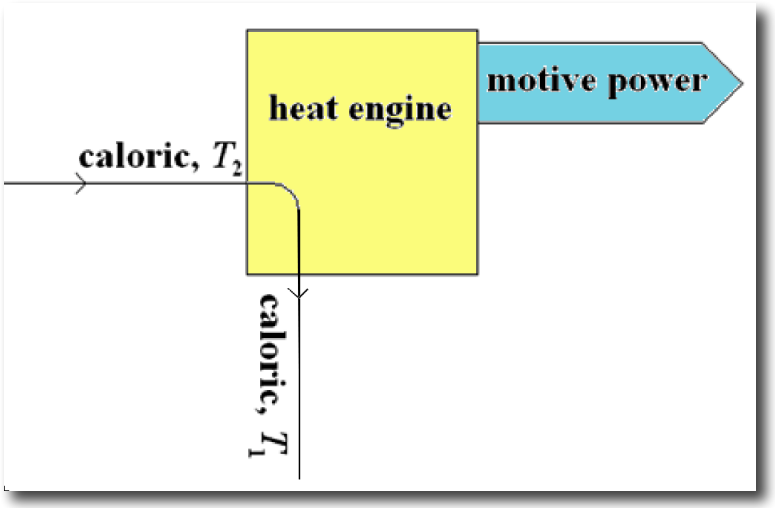


https://home.zhaw.ch/~fuh/COURSES/JO/Files_V/PER_Essay.pdf

2nd Chance




water wheel
motive power
mass, gh_2
mass, gh_1


heat engine
motive power
caloric, T_2
caloric, T_1

2nd Chance

Carnot's Engine Cycle

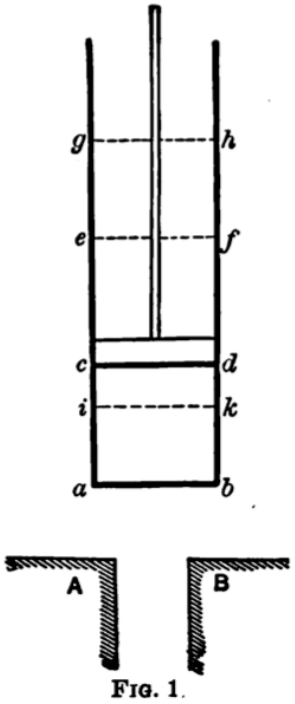
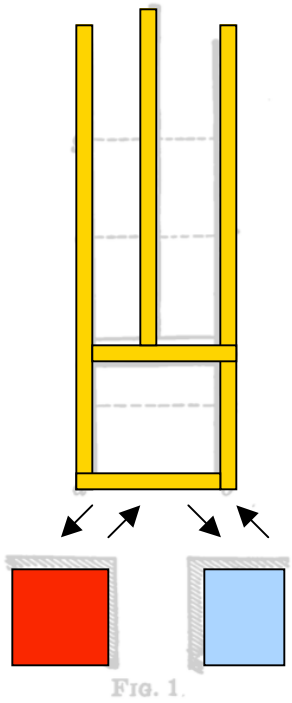
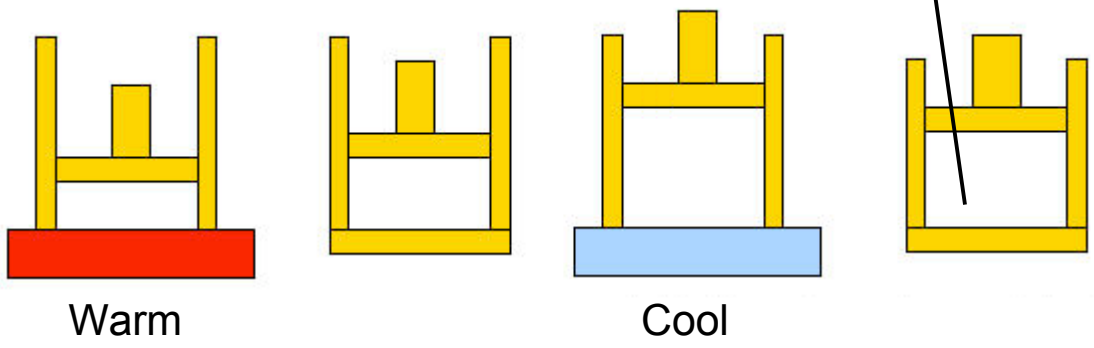


FIG. 1.

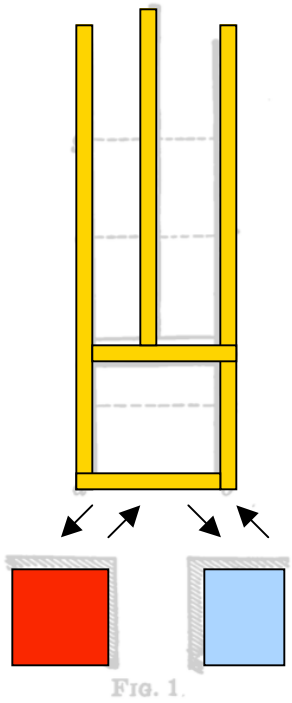
Carnot's Engine Cycle

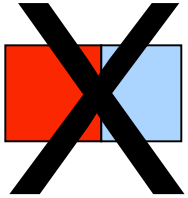




2nd Chance

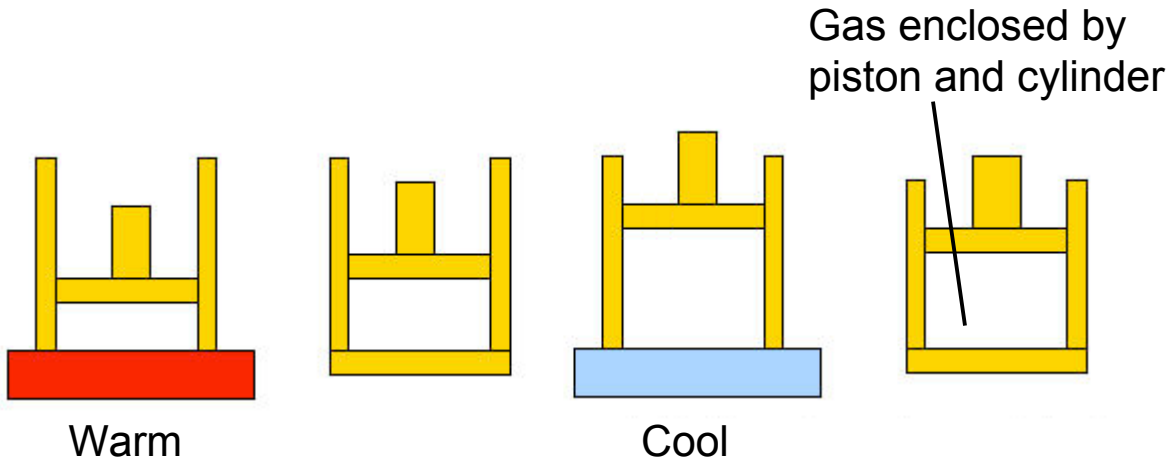
Carnot's Engine Cycle





Perfect reversible cycle:

No useless re-establishment of equilibrium -- "an actual loss"



Peripety

περιπέτεια: “a sudden change,
unexpected good fortune/misfortune“ in a drama

1842: Mayer's Heat Equivalent

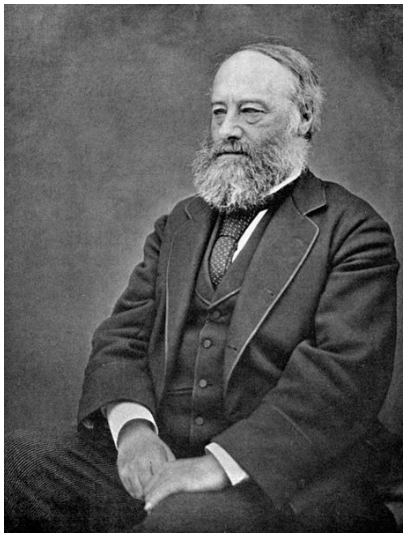
Peripety

Julius von Mayer
(1814-1878)

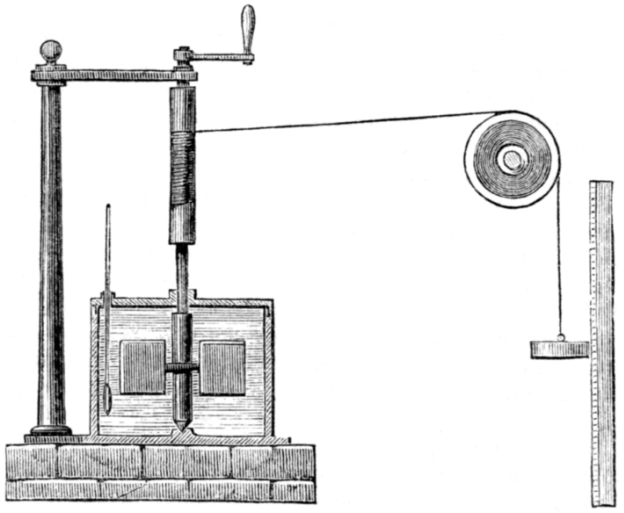
"The warming of a given weight of water from 0° to 1°C corresponds to the fall of an equal weight from the height of about 365 metres."

http://en.wikipedia.org/wiki/File:Julius_Robert_Mayer_von_Friedrich_Berrer.jpg
"Remarks on the Forces of Inorganic Nature," http://web.lemoyne.edu/~giunta/mayer.html

1843: Joule's Heat Equivalent



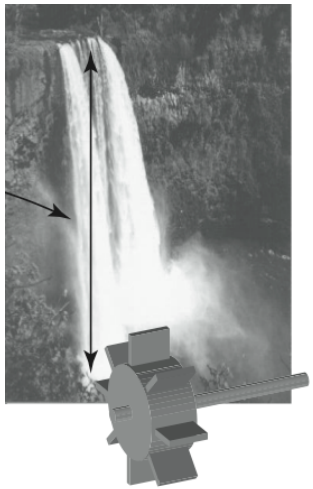
James Joule
(1814-1889)

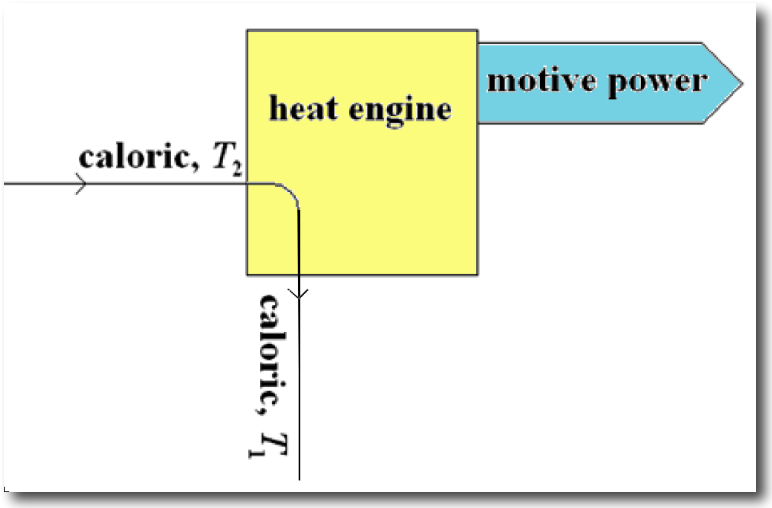


*"I [am] satisfied that the grand agents of nature are, by the Creator's fiat, **indestructible**; and that wherever mechanical force is expended, an exact equivalent of heat is **always** obtained."*

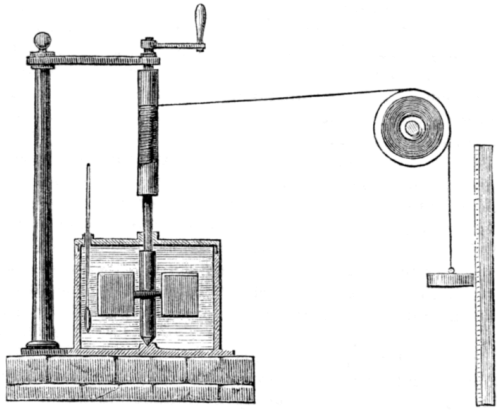
http://en.wikipedia.org/wiki/File:Joule_James_sitting.jpg
"On the Calorific Effects of Magneto-Electricity, and On the Mechanical Value of Heat"

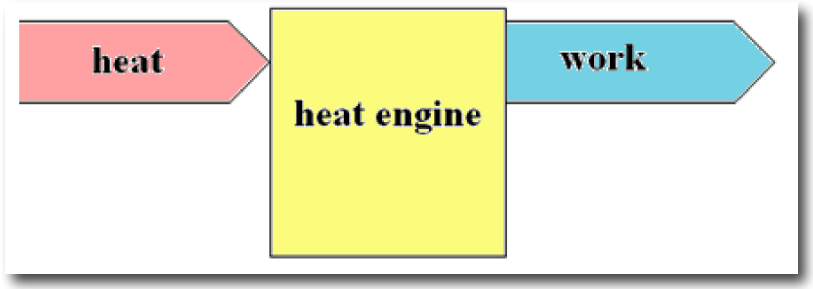
Carnot model





Mayer-Joule model





1848: Kelvin's "Absolute Thermometric Scale"

Peripety

*"The conversion of heat (or **caloric**) into mechanical effect is probably impossible*, certainly undiscovered.*

*" * This opinion seems to be universally held by those who have written on the subject. A contrary opinion however has been advocated by Mr. Joule of Manchester."*

Lord Kelvin
(William Thomson)
(1822-1888)

1849: Kelvin Re-interprets Carnot

Peripety

"When 'thermal agency' is…spent conducting heat through a solid, what becomes of the mechanical effect which it might produce? Nothing can be lost in the operations of nature — no energy can be destroyed."

Lord Kelvin
(Benjamin Thomson)
(1822-1888)

1849: Kelvin Re-interprets Carnot

Peripety

"When 'thermal agency' is…spent conducting heat through a solid, what becomes of the mechanical effect which it might produce? Nothing can be lost in the operations of nature — no energy can be destroyed."

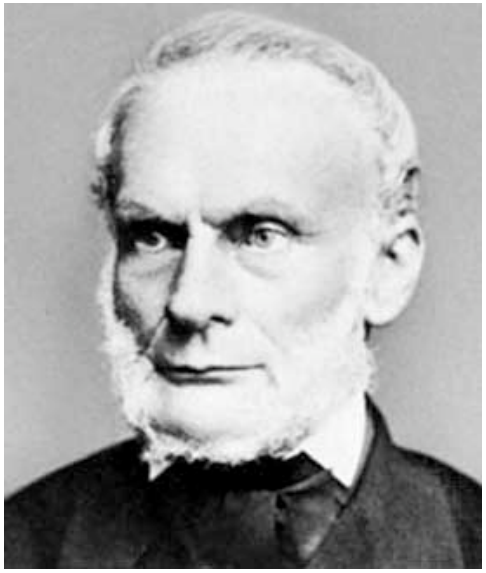
First modern use of "energy"

Lord Kelvin
(Benjamin Thomson)
(1822-1888)

1850: Clausius Integrates Joule and Kelvin

Peripety

”It is not even requisite to cast the theory of Carnot overboard…It is quite possible that in the production of work…a certain portion of heat may be consumed, and a further portion transmitted from a warm body to a cold one; and both portions may stand in a certain definite relation to the quantity of work produced.”



Rudolf Clausius

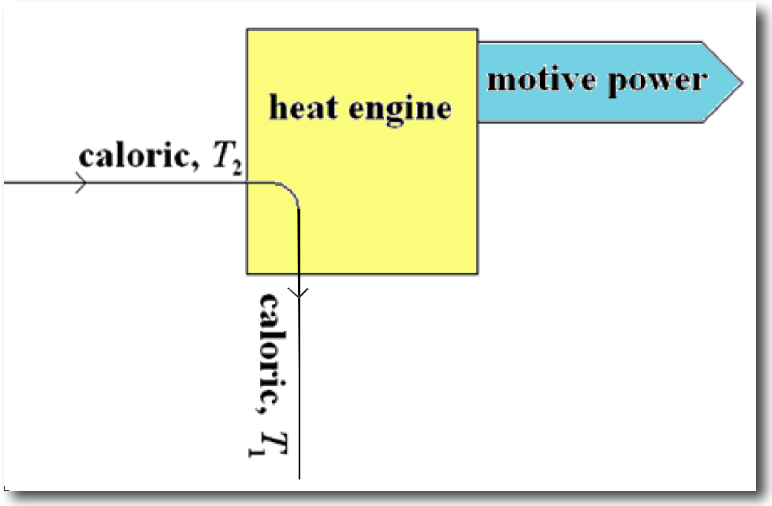
(1822-1888)

“On the Moving Force of Heat and the Laws of Heat which may be Deduced Therefrom“
http://en.wikipedia.org/wiki/File:Clausius.jpg

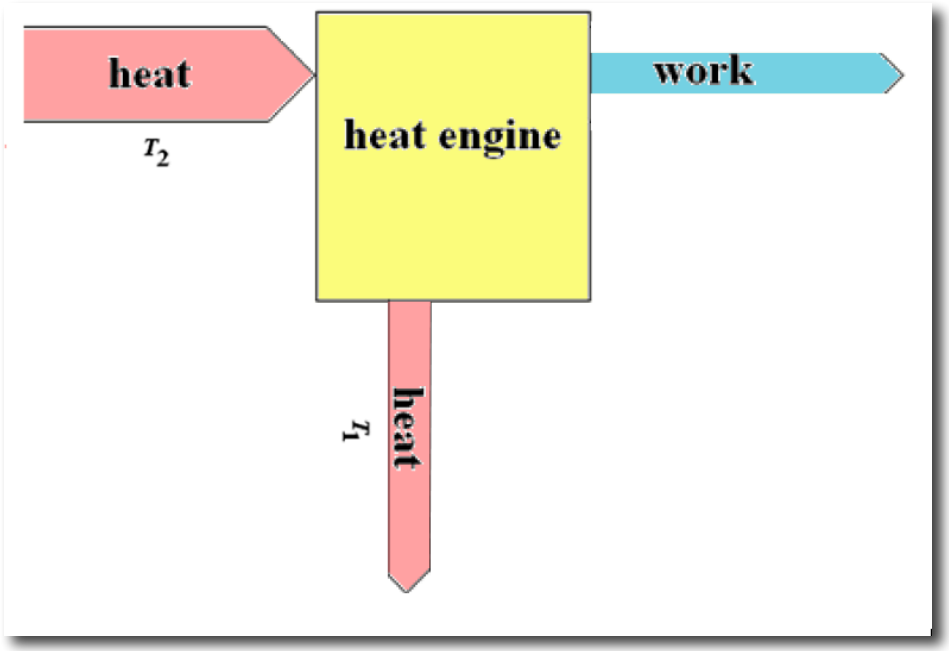
1850: Clausius Integrates Joule and Kelvin

Peripety

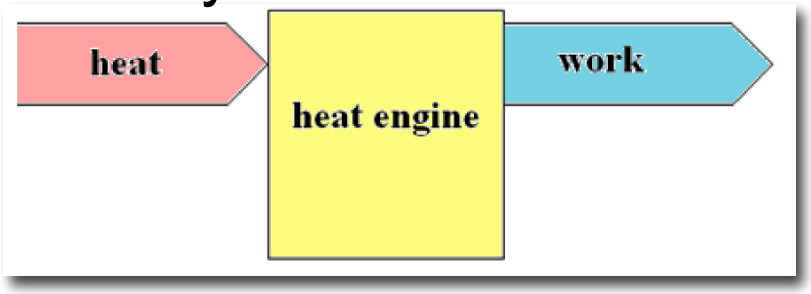
Carnot model



Clausius model



Mayer-Joule model



1851: Kelvin Agrees with Clausius

Peripety

"Heat is not a substance, but a dynamical form of mechanical effect."

Lord Kelvin
(Benjamin Thomson)
(1822-1888)

1852: Kelvin Explains “Waste”

“As it is most certain that Creative Power alone can either call into existence or annihilate mechanical energy, the ‘waste’…cannot be annihilation, but must be some transformation of energy.”

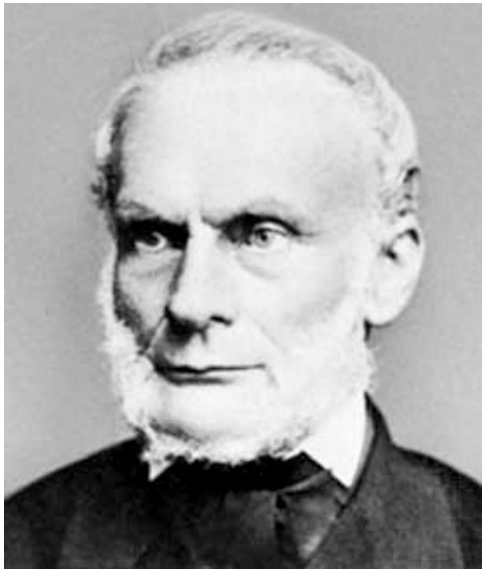
Lord Kelvin
(Benjamin Thomson)
(1822-1888)

1854: Clausius Defines “Equivalence-Value”

Peripety

$$\int \frac{dQ}{T} = 0$$

”The generation of the quantity of heat [energy] Q of the temperature T from work, has the equivalence-value Q/T.”



Rudolf Clausius
(1822-1888)

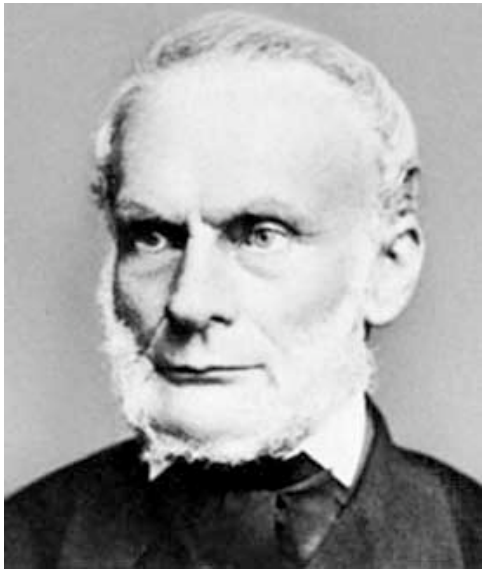
1864: Clausius Re-names it “Entropy”

Peripety

$$\int \frac{dQ}{T} = 0$$

$$\int \frac{dQ}{T} = S - S_0$$

"I propose to call the magnitude S the *entropy* of the system, after the Greek word τροπὴ , *transformation* …to be as similar as possible to the word *energy*: for the two magnitudes to be denoted by these words are so nearly allied in their physical meanings, that a certain similarity in designation appears to be desirable."



Rudolf Clausius
(1822-1888)

H.L. Callendar
(1863 – 1930)

3rd Chance

H.L. Callendar
(1863 – 1930)

J.J. Thompson
(1856 - 1940)

Platinum resistance thermometer
-160°C to 1600°C

http://www.chemheritage.org/discover/chemistry-in-history/themes/atomic-and-nuclear-structure/thomson.aspx
"The Callendar Effect," Fleming 2009

The Callendar Steam Tables, 1915

H.L. Callendar

(1863 – 1930)

TABLE VI.—ENTROPY Φ OF SUPERHEATED OR SUPERSATURATED STEAM IN THERMAL UNITS PER DEGREE, CENTIGRADE OR FAHRENHEIT.

Temperature. C.	F.	Pressure in pounds per sq. in. (Kg. per sq. cm. in Italics.) 20 *1·4061*	30 *2·1092*	40 *2·8123*	50 *3·5154*	60 *4·2185*	70 *4·9215*	80 *5·6246*	90 *6·3276*	100 *7·0307*
500	932	07640	03158	99974	97300	95465	93762	92274	90960	89785
450	842	04439	99932	96762	94283	92252	90534	89040	87721	86540
400	752	01003	96508	93310	90823	88784	87068	85556	84229	83040
390	734	00284	95787	92587	90098	88057	86329	84825	83496	82305
380	716	99555	95055	91853	89362	87319	85589	84082	82751	81558
370	698	98813	94310	91107	88613	86567	84835	83326	81993	80797
360	680	98061	93557	90350	87853	85805	84071	82559	81223	80025
350	662	97294	92787	89577	87078	85028	83290	81776	80437	79236
340	644	96515	92005	88792	86290	84236	82495	80978	79636	78432
330	626	95724	91211	87995	85489	83432	81688	80168	78822	77615
320	608	94919	90402	87182	84673	82613	80865	79341	77992	76781
310	590	94099	89578	86354	83841	81777	80025	78497	77144	75929
300	572	93264	88739	85511	82993	80924	79168	77636	76278	75059
290	554	92416	87886	84653	82131	80057	78296	76759	75397	74173
280	536	91551	87016	83778	81250	79171	77405	75863	74495	73266
270	518	90667	86126	82882	80349	78264	76492	74944	73571	72336
260	500	89768	85221	81970	79431	77340	75562	74007	72627	71386
250	482	88850	84296	81038	78492	76393	74607	73046	71660	70411
240	464	87914	83352	80087	77532	75426	73633	72064	70670	69413
230	446	86957	82386	79112	76549	74434	72632	71054	69651	68386
220	428	85980	81399	78116	75543	73418	71607	70019	68607	67332
210	410	84979	80388	77094	74510	72375	70553	68955	67531	66246
200	392	83957	79354	76048	73452	71305	69471	67861	66426	65128
190	374	82912	78295	74975	72366	70206	68358	66734	65286	63975
180	356	81839	77208	73873	71249	69073	67210	65572	64108	62782
170	338	80740	76092	72740	70099	67906	66026	64371	62890	61547
160	320	79612	74944	71573	68913	66702	64803	63128	61628	60266
150	302	78454	73765	70372	67690	65457	63530	61840	60319	58935
140	284	77264	72550	69133	66427	64170	62225	60504	58958	57550
130	266	76038	71297	67852	65118	62832	60839	59111	57537	56101
120	248	74776	70002	66525	63759	61442	59437	57656	56050	54583
110	230	73473	68663	65149	62347	59993	57952	56134	54492	52988
100	212	72127	67275	63720	60876	58479	56396	54538	52852	51307
Saturation Temperature	C.	108·87	121·28	130·67	138·30	144·79	150·46	155·52	160·09	164·28
	F.	*227·97*	*250·31*	*267·21*	*280·94*	*292·62*	*302·83*	*311·93*	*320·16*	*327·71*

The characteristic (or figure before the decimal point) and the decimal point are omitted. The characteristic is always unity, except for the first four values under 20 lbs., and the first only under 30 lbs., for which the characteristic is 2.

The entropy is the same in all systems of units.

36

3rd Chance

1911: Callendar Re-argues Carnot

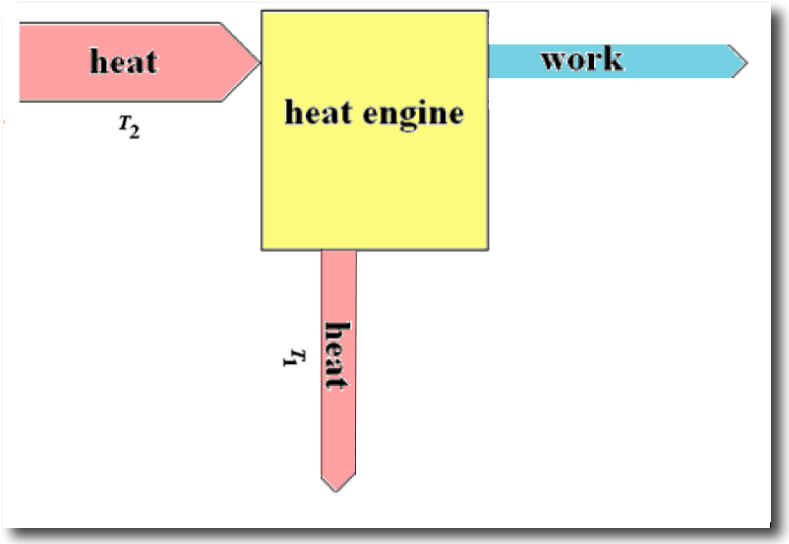
"Clausius gave it the name 'entropy,' and defined it as the integral of dQ/T. Such a definition appeals to the mathematician only. In justice to Carnot, it should be called caloric…Even the mathematician would gain by thinking of caloric as a fluid, like electricity, capable of being generated by friction or other irreversible processes."

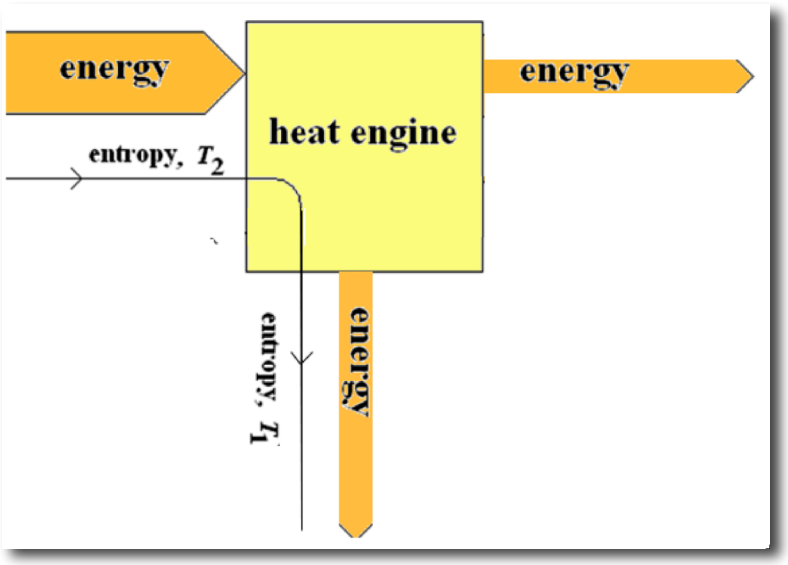
$$\int \frac{dQ}{T} = S - S_0$$

1911: Callendar Re-argues Carnot

"We have become so saturated with the idea that heat is energy…that we…forget that a quantity of heat is not completely specified by its energy equivalent…

"It is true that we can solve most questions in heat in terms of energy and temperature, without explicit reference to caloric or [entropy]. We could similarly solve most electrical problems without mentioning amperes. But…[everything is] greatly simplified and rendered more direct if we adopt caloric as the true measure of heat quantity and regard it as possessing energy in virtue of its temperature."





3rd Chance

1938: Son Establishes “The Callendar Effect”

551.510.4 : 551.521.3 : 551.524.34

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. Dobson, F.R.S.)

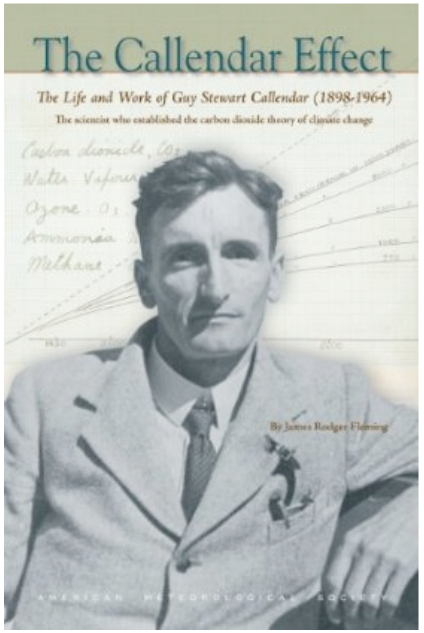
[Manuscript received May 19, 1937—read February 16, 1938.]

SUMMARY

By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on “ sky radiation.” From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0·003°C. per year at the present time.

The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0·005°C. per year during the past half century.

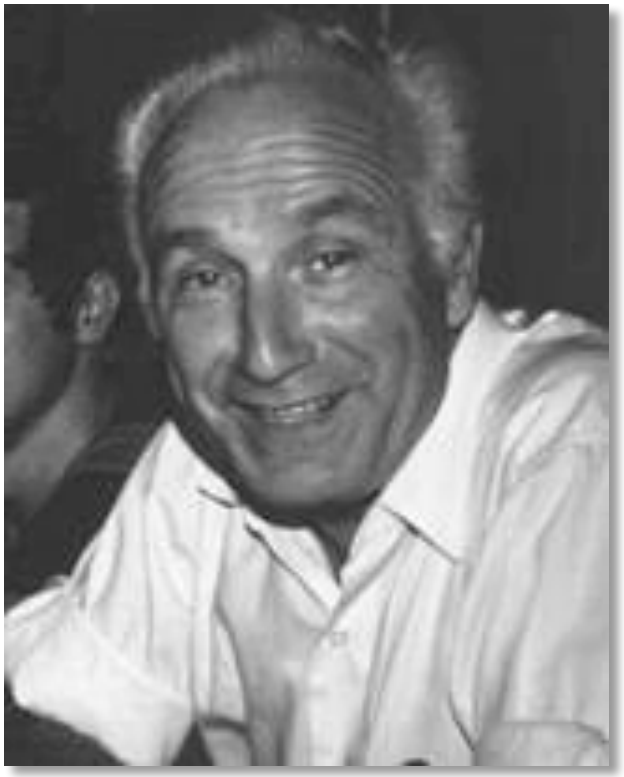


G.S. Callendar

(1898-1964)

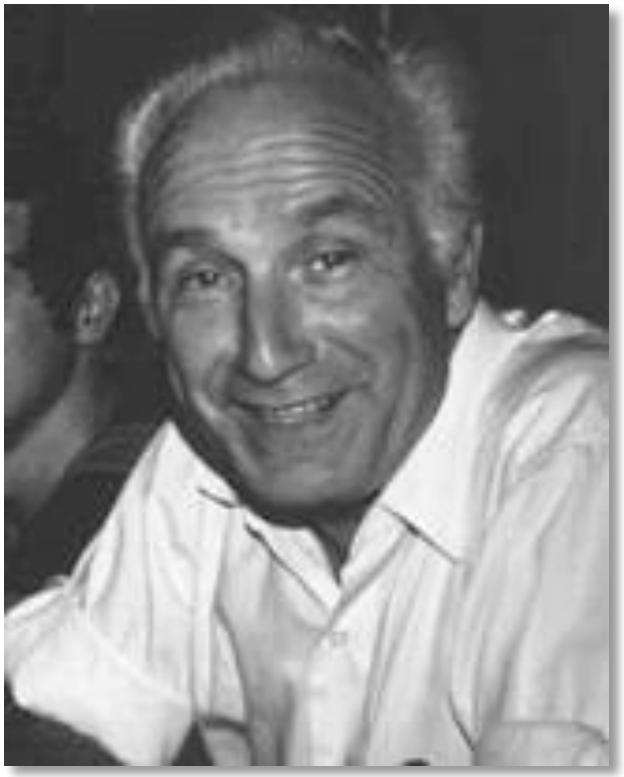
http://wiki.nsdl.org/index.php/PALE:ClassicArticles/GlobalWarming/Article6

The Callendar Effect: The Life and Work of Guy Stewart Callendar (1989-1964), The scientist who established the carbon dioxide theory of climate change, James Rodger Fleming, 20098

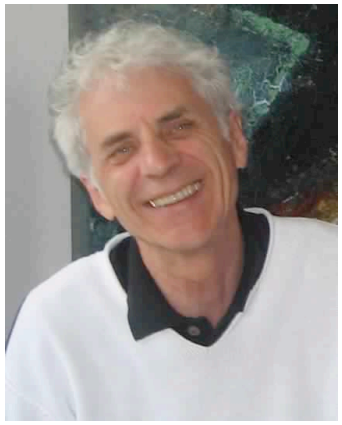


Gottfried Falk
(1922 – 1990)

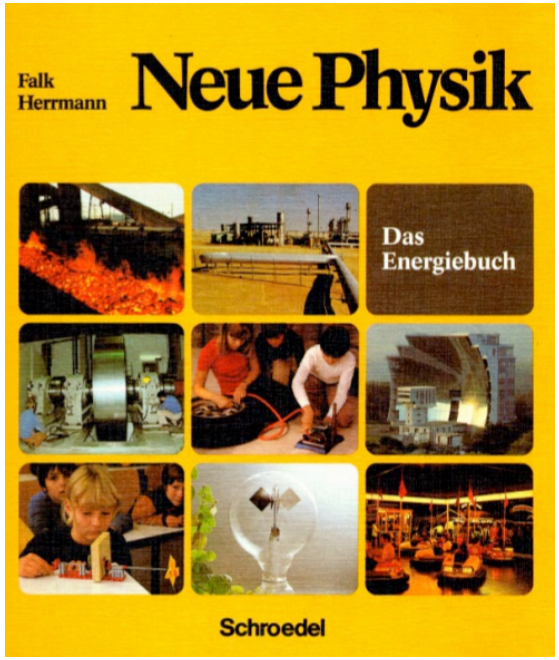
Encore



Gottfried Falk
(1922 – 1990)



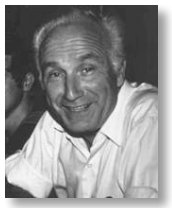
Friedrich Herrmann

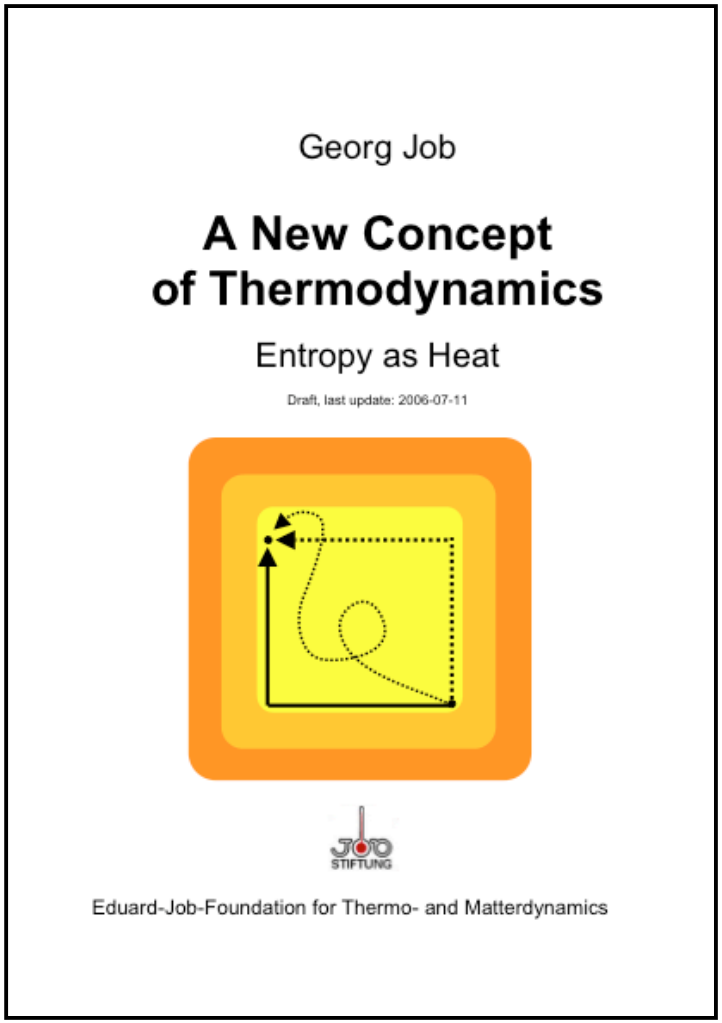


http://www.physikdidaktik.uni-karlsruhe.de/Kontakt/Kontakt.html
http://www.physikdidaktik.uni-karlsruhe.de/kpk/Energiebuch.pdf

Georg Job

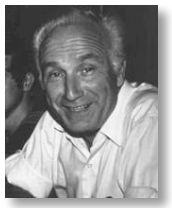
Encore





Georg Job

Encore



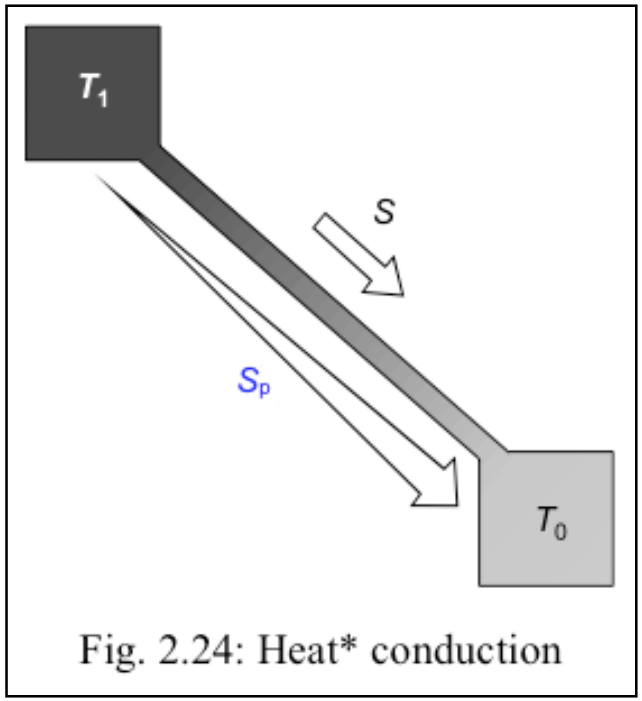
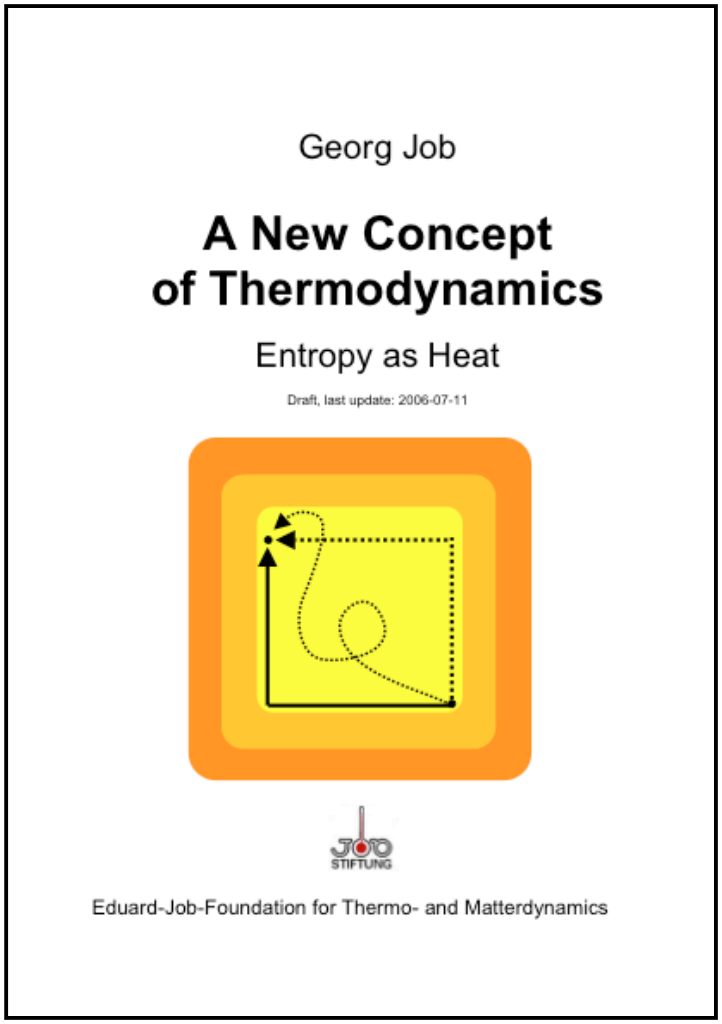
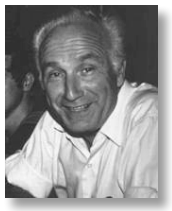


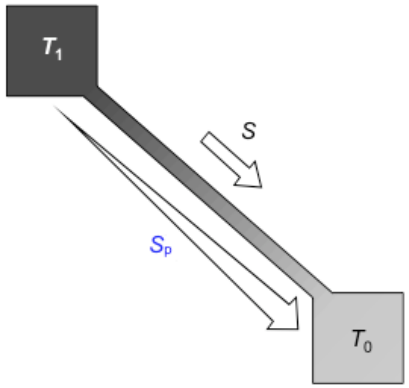
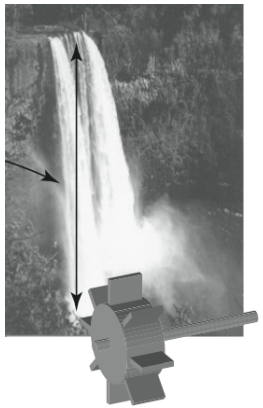
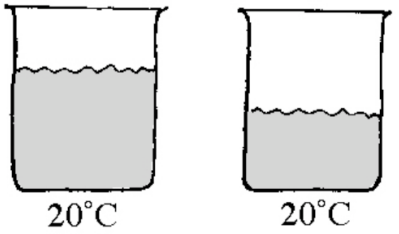
Fig. 2.24: Heat* conduction



1985: Falk's Synthesis

Encore

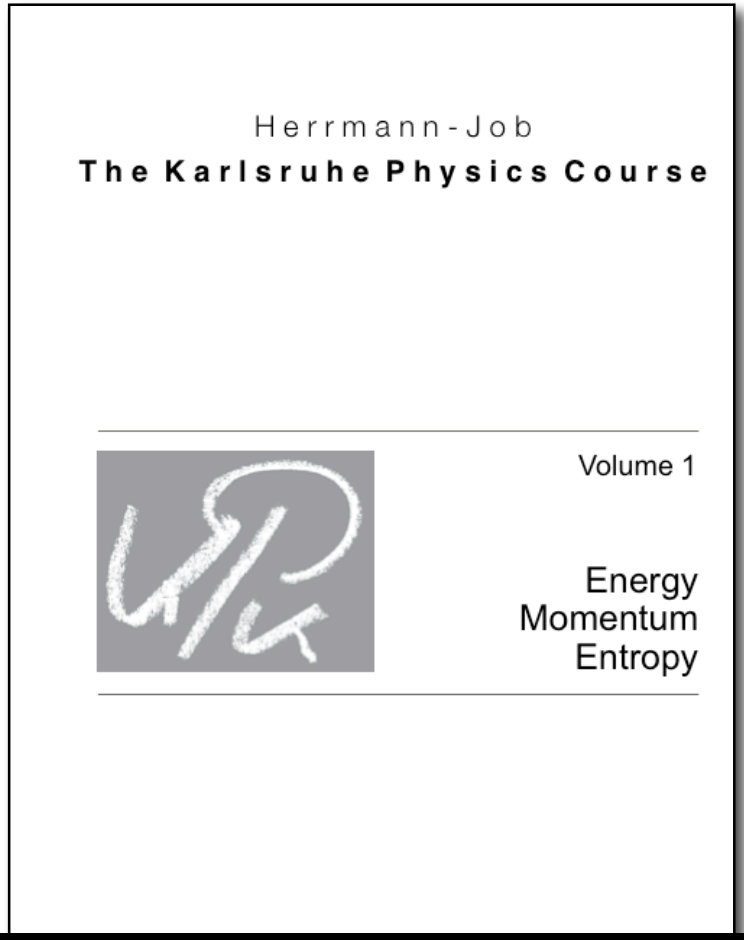


Job's "Entropy"	Carnot's "Caloric"	Black's "Quantity of heat"
 Fig. 2.24: Heat* conduction		

"Entropy can be visualised as a kind of substance which obeys 'half a conservation theorem': it can be created but not destroyed."

Exodus

Exodus



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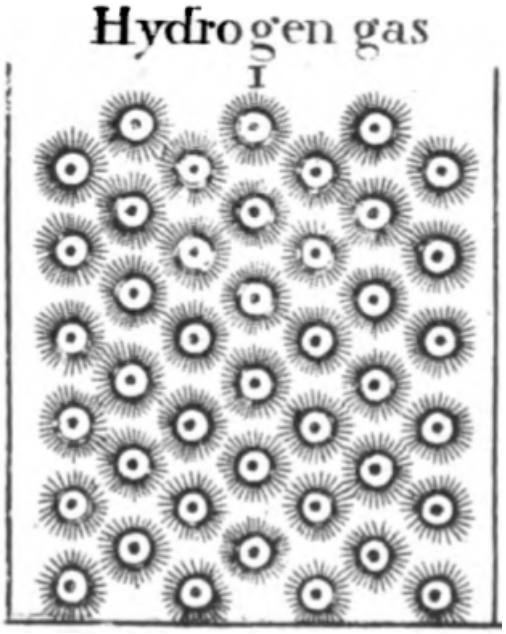
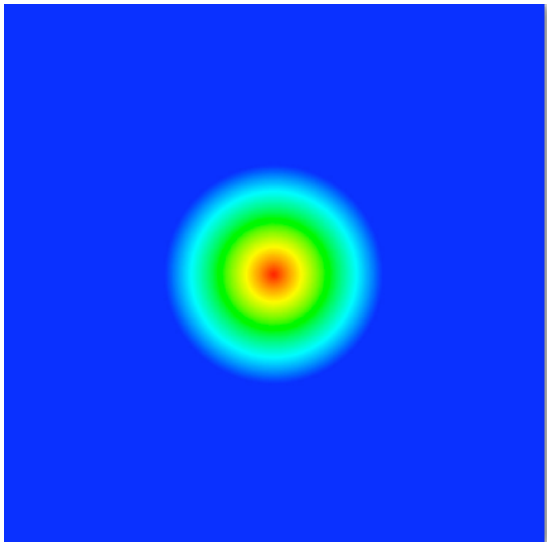
http://www.physikdidaktik.uni-karlsruhe.de/publication/pub_fremdsprachen/englisch.html

Exodus



Caloric

Hydrogen atom



Electrons and protons

http://www.physikdidaktik.uni-karlsruhe.de/software/hydrogenlab/

"Macroscopic entropy" ***complements*** the statistical mechanical interpretation

Ludwig Boltzmann
(1844 - 1906)

S = k log W

"The logarithm of a probability of a complexion"

Exodus

Entropy is ***hugely*** important for solving our energy and climate problems.

http://atlasobscura.com/place/boltzmanns-grave

Exodus

Entropy is ***hugely*** important for solving our energy and climate problems.

We have one more chance, maybe the last one.

Let us see if we can find a way to live with entropy.

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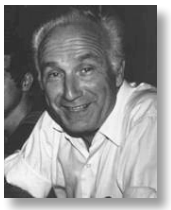
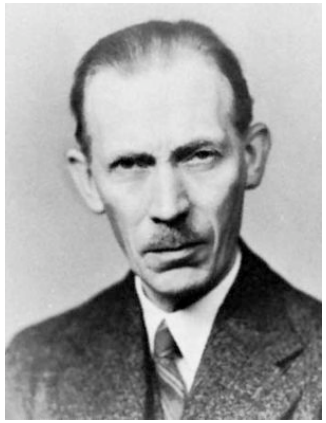
Encore



Wilhelm Ostwald
(1853-1932)



Johanne Brønsted
(1879-1947)

Victor La Mer
(1895-1966)

Thomas Kuhn
(1922-1996)

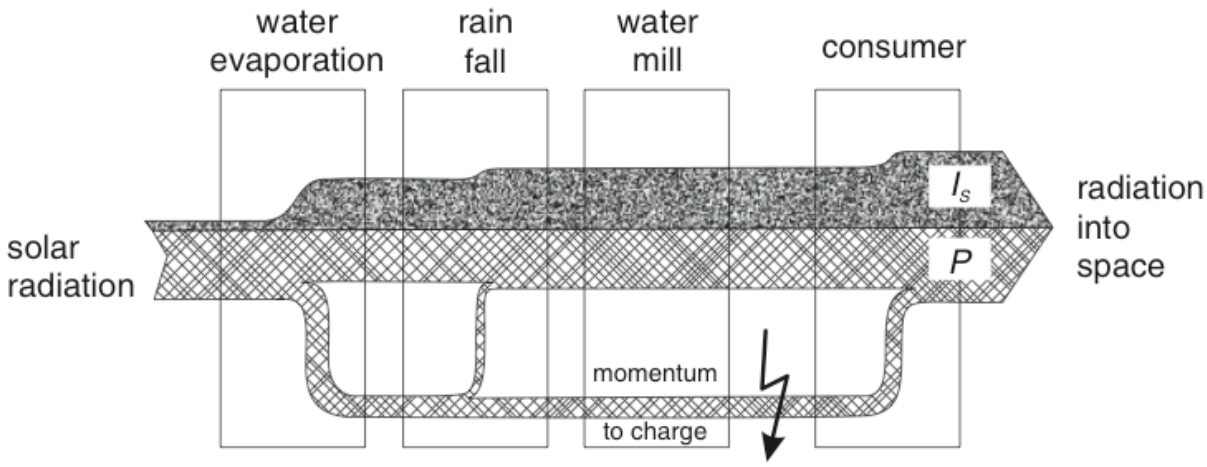
TABLE I. Interpretation of Carnot's terms.

Carnot (1824)	Kelvin (1849–52)	Clausius (1850)	Thurston (1890) Magie (1899) (translation)	Ostwald (1892) (translation)	Brønsted (1937)
feu	heat	wärme	heat	feuer	(none given)
chaleur			heat	wärme	heat
calorique			caloric	wärmestoff	entropy

http://colloidssurfaces.org/victor-k-lamer-award/
http://thomas-kuhn.blogspot.com/

“Renewable energy sources in terms of entropy”

Jan-Peter Meyn, European Journal of Physics, 2011



1842: Mayer's Heat Equivalent

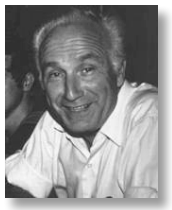
Peripety

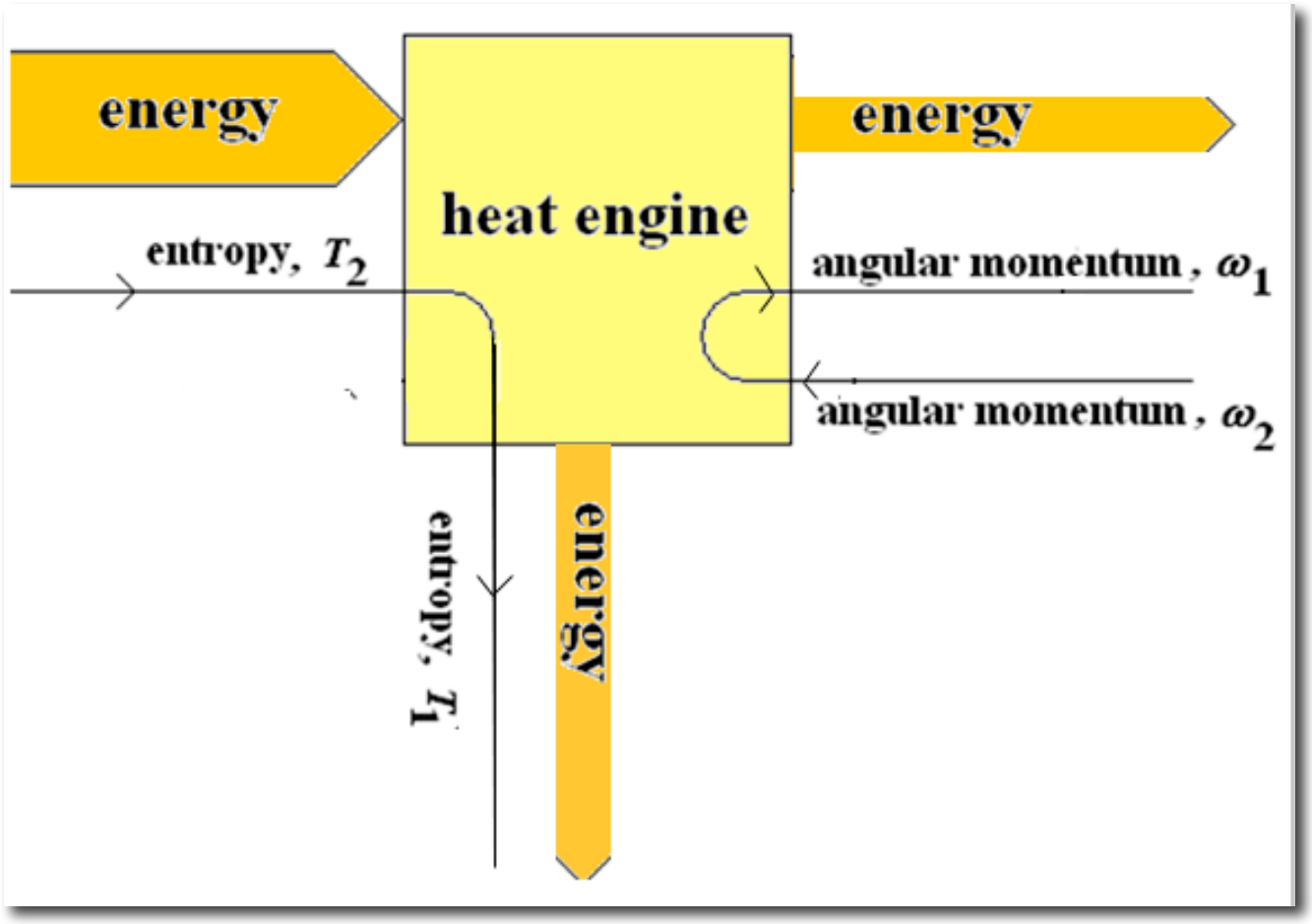
Julius von Mayer
(1814-1878)

"The warming of a given weight of water from 0° to 1°C corresponds to the fall of an equal weight from the height of about 365 metres. If we compare with this result the working of our best steam-engines, we see how small a part only of the heat applied under the boiler is really transformed into motion or the raising of weights; and this may serve as justification for the attempts at the profitable production of motion by some other method than the expenditure of the chemical difference between carbon and oxygen--more particularly by the transformation into motion of electricity obtained by chemical means."

http://en.wikipedia.org/wiki/File:Julius_Robert_Mayer_von_Friedrich_Berrer.jpg
"Remarks on the Forces of Inorganic Nature," http://web.lemoyne.edu/~giunta/mayer.html

Encore




energy
heat engine
energy
entropy, T_2
angular momentum, ω_1
angular momentum, ω_2
entropy, T_1
energy

1799: Davy's Ice Friction Experiment

1st Chance

Humphry Davy
(1778 – 1829)

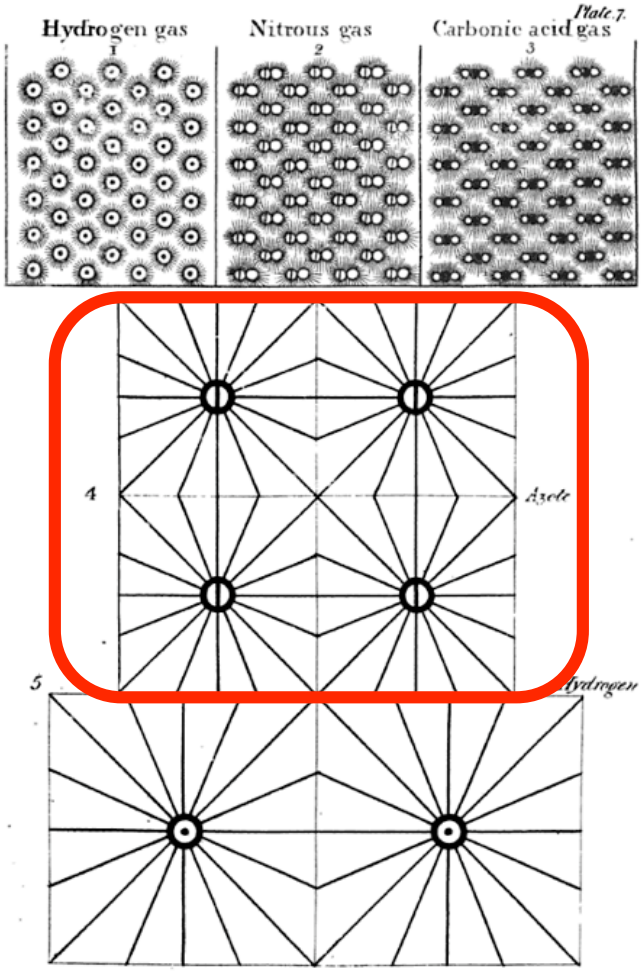
"It has then been experimentally demonstrated that caloric, or the matter of heat, does not exist…

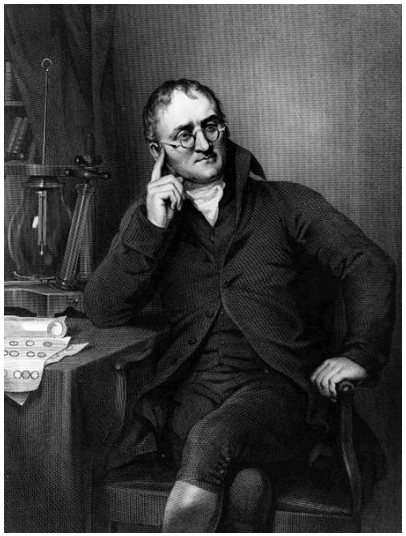
"Heat…may be defined a peculiar motion, probably a vibration, of the corpuscles of bodies, tending to separate them."

http://progressivewriter.blogspot.com/2011/04/scientists-birbel-shagani-sir-humphry.html
"On Heat, Light, and the Combinations of Light", http://books.google.com/books?id=jd9LAAAAYAAJ

1808: Dalton's Elastic Atmospheres

1st Chance



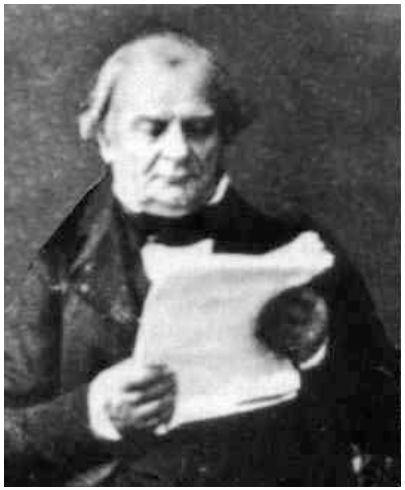


John Dalton
(1766 – 1844)

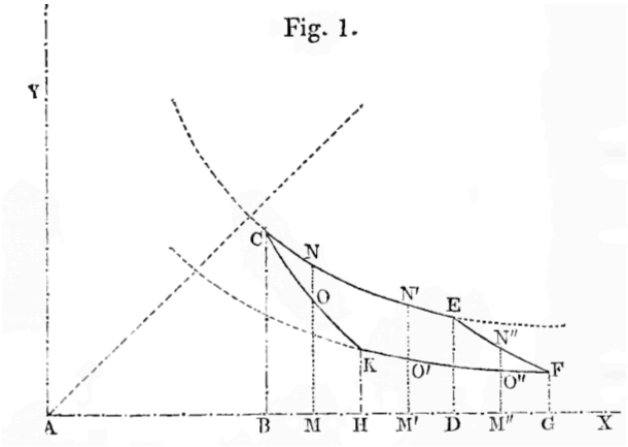
"4 particles of azote with their elastic atmospheres, marked by rays emanating from the solid central atom; these rays being exactly alike in all the 4 particles, can meet each other, and maintain an equilibrium."

1834: Clapeyron Re-interprets Carnot

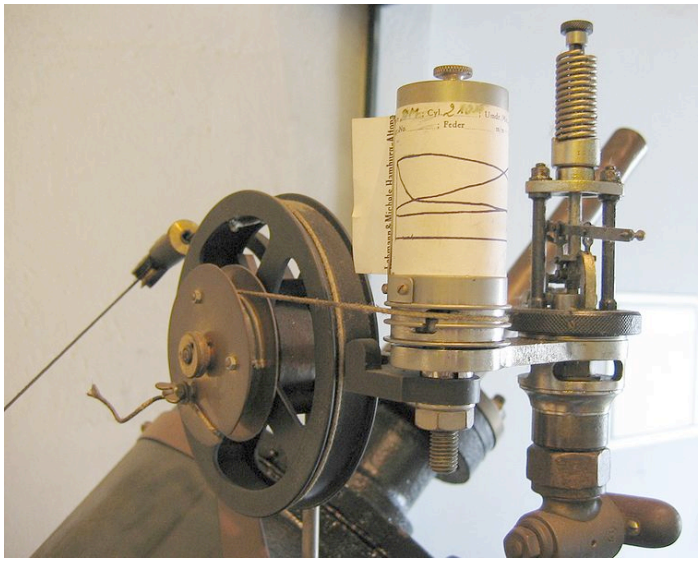
2nd Chance



Émile Clapeyron
(1814-1878)



Clayperon's diagram



Watt's Engine Indicator

"Memoir on the Motive Power of Heat"
http://commons.wikimedia.org/wiki/File:Indikator_Dampfmaschine.jpg

H.L. Callendar
(1863 – 1930)

"The more shadowy the conception to be visualized, the greater the need of a definite material analogy."

http://atlasobscura.com/place/boltzmanns-grave